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REEFING OF PARACHUTES

DRAG AREA RATIOS VS REEFING RATIOS

AERONAUTICAL SYSTEMS DIVISION
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

JULY 1976

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REEFING OF PARACHUTES–DRAG AREA RATIOS VS REEFING RATIOS

DIRECTORATE OF EQUIPMENT ENGINEERING

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DEPUTY FOR ENGINEERING
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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Reefing data were collected and evaluated for the following parachute types: solid circular parachutes of flat, conical, and triconical design; extended skirt parachutes of 10 percent flat extended, 10 percent straight extended, and fully extended (14.3 percent) design; and slotted parachutes of ringslot, Ringsail, and flat and conical ribbon design. Various reefing terminologies are discussed that have been used in the past and a recommendation is made for a common terminology. Background data are provided for all parachutes analyzed. (cont)

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20. Cont

Drag area ratios vs reefing ratios are listed in tables and shown in individual graphs and in a summary chart for all parachutes investigated.

FOREWORD

This Technical Report was prepared by Mr. T. W. Knacke as a consultant to the Division Advisory Group (DAG), of the USAF Aeronautical Systems Division (ASD), Wright-Patterson AFB, Ohio. Management supervision was provided by the Chief of the ASD Parachute Branch, Mr. Herman Engel. Mr. Solomon Metres and Mr. James DeWeese of the Flight Dynamics Laboratory, Recovery and Crew Station Branch, together with Mr. H. Engel formed a team directing the technical efforts.

The author wishes to acknowledge and express his appreciation for the cooperation of Mr. James Reuther of the Pioneer Parachute Company, Mr. William Lewis of the US Army Natick Laboratories, the Northrop Corporation - Ventura Division, Mr. William Pepper of the Sandia Corporation, and Mr. Oscar Sepp of the ASD B-1 System Project Office. These people either provided data used in this report or helped to confirm existing data.

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Symbol	Concept	Dimensions
C_{D_o}	drag coefficient of a parachute canopy based on surface area S_o	none
C_{D_R}	drag coefficient of a reefed parachute based on surface area S_o	none
D_o	nominal diameter of parachute canopy, $D_o = \sqrt{\frac{4 S_o}{\pi}}$	feet
D_R	diameter of a circle formed by the reefing line in a reefed parachute canopy	feet
D_{R_o}	diameter of a circle formed by the reefing line of a full open parachute canopy (reference length only)	feet
L_R	installed length of a reefing line	feet
L_{R_o}	installed length of a reefing line of a full open parachute canopy (reference length only)	feet
N_G	number of gores in a parachute canopy	none
N_{SL}	number of suspension lines of a parachute	none
q	dynamic pressure	psf
S_o	total one-sided surface area of a parachute canopy including vent and openings of slotted canopies	ft^2
$(C_D S)_o$	drag area of a full inflated parachute	ft^2
$(C_D S)_R$	drag area of a reefed parachute	ft^2
C	ratio between suspension line circle of a full inflated parachute canopy (D_{R_o}) and nominal parachute diameter D_o	none
V	velocity	ft/sec
V_{e_o}	sea level rate of descent	ft/sec
α	angle of attack	degrees
ε =	$\frac{(C_D S)_R}{(C_D S)_o}$ = drag area ratio: ratio of reefed to unreefed parachute drag area	none
ρ =	density of air	$slugs/ft^3$
τ =	$\frac{D_R}{D_o}$ = reefing ratio: ratio of reefing line circle diameter D_R to nominal parachute diameter D_o	none

SECTION I

INTRODUCTION

The purpose of this report is to summarize data on the reefing of parachutes, especially the relationship of degree of reefing to the resultant reduction in parachute drag area. Data have been collected and analyzed for solid material parachutes of flat circular and conical design, for various types of extended skirt parachutes, and for slotted parachutes of ribbon, ringslot and ringsail design. Special emphasis was placed on obtaining reefing data that have not been published previously or are not available through the Defense Documentation Center (DDC).

Reefing methods investigated and reefing terminology used at various times in the past are discussed and evaluated.

Figures 2 to 10 give drag area ratios ξ versus reefing ratios τ for all previously mentioned parachutes. Figure 11 gives a summary of all reefing data. All plotted data are listed individually in tables 1 to 6 in a form that allows inclusion in the data bank of the USAF Flight Dynamics Laboratory.

Analysis and discussion of all data shows generally good agreement among results obtained under related, controlled conditions. There are limitations on the size of model parachutes that provide reefing test data applicable to full scale design. With few exceptions, out-of-line data can be traced to unusual test conditions, non-traceable designs, or to definition problems.

Recommendations are made for a common reefing terminology.

SECTION II

SYSTEMS AND DEFINITIONS

1. General

Reefing of parachutes, to the best knowledge of the author, was applied for the first time on ribbon parachutes in the summer of 1941. These parachutes were used for the approach and landing deceleration of German Ju 52 aircraft deployed in airborne landing operations (see Reference 1). The parachutes were reefed on landing approach and disreefed by pilot command at aircraft touchdown. The reefing system used restricted the canopy skirt inlet area with short lines attached on one side to each suspension line attachment point at the canopy skirt with the other end of the lines held in a disconnect device in the center of the canopy skirt. All lines were disconnected simultaneously by pilot command through firing of a charge in the disconnect device. This approach was soon replaced by the "Skirt Reefing with Control Line Method"[1] It was recognized early that reefing could be used advantageously for limiting the opening shock load of parachutes and for the stabilization of cargo containers dropped from high altitude with the parachutes reefed during high speed descent and disreefed prior to landing. That reefing is necessary for uniform inflation of large parachutes dropped in clusters was not established until 1948, when the USAF started to develop cluster parachute descent systems for heavy military equipment.

In 1943, the author of this report conducted an extensive investigation of more than a dozen different reefing concepts. This included several vent reefing methods, reefing concepts with lines placed around the canopy, the canopy skirt, and around the suspension lines at various distances from the skirt, and reefing methods with parts of the canopy held in a special bag. The most practical system evolved was the "Skirt Reefing Method," very much in the form as it is used today.

Another investigation of various reefing methods was conducted in 1960 in Great Britain by Walters, Cobb and Bonnett.[2] Again, the skirt reefing method, called "Rigging Point Reefing" in Great Britain, emerged as the most practical system.

Some unpublished investigations of reefing methods were conducted by the NASA Langley Research Center and by the USAF at Wright-Patterson AFB. The "Mid-Gore Reefing" method, a modification of the skirt reefing system, evolved from one of these USAF investigations. Most likely, other methods have been tested of which the author has no knowledge.

Reefing of a parachute for application in a recovery system generally starts with an analytical determination of the amount of reefing required. Today this is accomplished in computer runs where the number of reefing stages, drag area reductions, and staging times

are determined dependent on such requirements as maximum allowable system deceleration, load balance in reefing stages, and available altitude-time sequence. The second step then involves the dimensioning of the reefing system. If skirt reefing is used it means the determination of the installed length and strength of the reefing line(s) and of such system components as reefing rings, reefing cutters, etc. As already stated, the primary purpose of this report is the presentation of data for calculating the required length of the reefing line. Length of reefing line, as used in this report, means installed length. One frequently hears the comments, "We do not have sufficient data for determination of the required reefing line length!" This is an incorrect statement, as the great amount of data presented in this report will show. Unfortunately, many data that are available in company reports are not available to the technical community in general. The two most typical examples are the large amount of reefing data collected on the parachute systems for the Mercury, Gemini, and Apollo spacecrafts and on the parachute system for the B-1 aircraft crew module recovery system. The author has obtained these and other unpublished reefing data but makes no claim of having obtained all the data available in company or government agency files. Many data remain also incomplete or lacking in some vital details.

2. Reefing Systems

This paragraph describes and analyzes the most commonly used reefing systems.

a. Skirt Reefing

Skirt reefing, by far the most commonly used form of reefing, is sufficiently known to make a detailed description unnecessary. Figure 1.a shows a view into the parachute canopy. Each confluence point of suspension line and canopy skirt has a reefing ring attached, with two or more reefing cutters located at several equally spaced points around the canopy. The diameter of the circle formed by the installed reefing line is defined as reefing diameter D_R. For reliability reasons, two or more reefing cutters are used. This assures that the reefing line is cut even if one of the cutters fails to function. It may be of interest to mention that the Apollo main parachute system used two reefing lines and two reefing cutters per line in the first reefing stage.[3] This assured proper functioning of the system within prescribed reliability limits, in case one reefing cutter did not fire, but also for the case that one reefing line was cut prematurely. The extreme high reliability requirement of the Apollo parachute system, which was the primary means of earth landing for the astronauts, made this complex approach mandatory.

b. Mid-Gore Reefing

Mid-Gore reefing is a modification of skirt reefing developed by the Parachute Branch of the USAF Aeronautical Systems Division at Wright-Patterson AFB, Ohio. Figure 1.b shows the arrangement looking into the skirt of the parachute. The reefing rings are attached to the skirt of the parachute in the center of each gore instead of the suspension line-canopy attachment points. This provides for double the restraining points, as can be seen from Figure 1.b, and thus for less flutter of the uninflated parts of the reefed parachute canopy. The result is a more uniform inflation process and a more uniform reefed drag area of individual cluster parachutes. The unusual inflation characteristics of reefed Ringsail parachutes caused non-uniform inflation of the three Apollo main parachutes; mid-gore reefing was one of the means that improved uniform cluster inflation. To the best of the author's knowledge, the Apollo parachute system so far is the only operational application of mid-gore reefing.

It was found that for the same length of installed reefing line - that is, for the same reefing ratio - a slightly larger drag area was obtained with mid-gore reefing than with skirt reefing. The only data available on mid-gore reefing were obtained on Ringsail parachutes in the Apollo program, see Figure 8 and References 4 and 5.

c. Vent Reefing

Another reefing method that has found some application is commonly called vent reefing. This concept attaches a centerline to the inside of the canopy vent[1]; pulling this line in the direction of flight toward the confluence point of the suspension lines first forms a half toroid and then turns the canopy inside out. Adjusting the centerline at the level of the skirt results in an increase in inflated canopy diameter and a concomitant increase in drag of approximately 30 percent.[1, 6] This phenomenon is used in the design of the Airfoil and Annular parachutes for obtaining high drag. Tests with parachutes, vent-reefed to a low drag area, which means with the vent pulled way down, showed a high rate of undesirable flutter. It also was impossible to obtain drag area ratios of less than approximately 0.1 prior to a position where individual suspension lines would flap over and entangle the parachute canopy.

Comment: The author is aware of numerous attempts to develop "Continuous Disreefing" systems and is cognizant of the "Schade" reefing system used for Hi-Glide steerable sport parachutes; however, he considers these systems beyond the scope of this report.

Reefing Definitions

Several methods have been used in the past for defining the relationship of reefing line length to drag area decrease. The first method, described in Reference 1, is called the "1947 Method" for purposes of definition.

An improved method was published in the second edition of the USAF Parachute Handbook.(6) In this report it is called the "D_{R1}/D_{R_o} Method." The third method, called the "D_R/D_o Method," used most frequently in recent years, is considered the simplest and most accurate method, and is, therefore, recommended for future use.

a. The 1947 Method

The 1947 Method used by the author in the first summary report on reefing(1) was based on aerodynamic considerations due to the limited number of reefing tests conducted prior to that time. The required known reefed drag area of a large parachute is used to calculate the diameter of an unreefed small parachute having the same drag area. The diameter of the suspension line circle (reefing line circle) of the full open small parachute can be calculated using a factor c which had been determined in wind tunnel tests. A small adjustment is then made for the difference of the reefing line diameter circle of the full open small parachute and the reefing line diameter circle of the large reefed parachute. This reasonably accurate but complex method was replaced in the second edition of the USAF Parachute Handbook(6) by the D_{R1}/D_{R_o} method.

b. The D_{R1}/D_{R_o} Method

The D_{R1}/D_{R_o} method evolved from a series of reefing tests on ribbon and solid flat parachutes conducted in the early 1950's at the Department of Defense El Centro Parachute Test Facility. The reefing line circle diameter of the full open parachute D_{R_o} was used as reference diameter for calculating the reefing line length. D_{R_o} must be calculated and varies with the type of parachute and the number of suspension lines N_{SL} of the individual parachute.

This method, simpler than the 1947 method, has the advantage that it results in a reefing ratio of 1.0 for the full open parachute, but it requires the knowledge of the ratio $\not{c}$ of reefing line diameter D_{R_o} of the full inflated parachute to the nominal diameter D_o. This introduces some inaccuracies.

It was only a question of time before the idea of using the nominal parachute diameter as reference diameter would be suggested. This approach is called the "D_R/D_o Method."

c. The D_R/D_o Method

Using the nominal diameter D_o as reference for the reefing line length has several advantages. The length of the reefing line is determined by defining the ratio of the reefing line diameter circle to the nominal diameter of the parachute called the reefing ratio τ . This ratio can easily be obtained in wind tunnel or free-flight tests from the known length of the installed reefing line, and thereby its reefing line circle diameter, and from the known nominal diameter of the parachute. It has one disadvantage which is of a more theoretical nature: the reefing ratio τ for the full open parachute is less than 1.0 and varies between 0.58 and 0.65, depending on the type of parachute and the number of suspension lines used.

The D_R/D_o Method was recommended by DOD organizations, companies, and individuals contacted in the preparation of this report. The following terms are used in the analysis part of this report:

$$\text{Drag Area Ratio } \xi = \frac{(C_D \cdot S)_R}{(C_D \cdot S_o)} = \frac{\text{Reefed parachute drag area}}{\text{Full open parachute drag area}}$$

$$\text{Reefing Ratio } \tau = \frac{D_R}{D_o} = \frac{\text{Diameter of reefing line circle}}{\text{Nominal parachute diameter}}$$

d. The C_R Method

Some investigators have defined a reefed drag coefficient C_R and have used the parachute surface area S_o as reference area. (11, 17) This definition agrees with the terminology used in testing drag and lift bodies in wind tunnel tests; however, it is less convenient for calculating reefing line dimensions. The reefing coefficient C_R depends on the individual parachute tested and varies among parachutes of the same type based on diameter, number of suspension lines, and porosity. It varies even more between parachutes of different types; for example, Ringsail and ribbon design; therefore, data cannot be used as ratios which is the preferred and simplest approach for predetermination of required reefed drag area. Plotting the data in the form of C_{D_R}/C_{D_o}, as some authors have done, is equivalent to the drag area ratio ξ . It produces the same results since both use the same reference area S_o.

SECTION III

DRAG AREA RATIOS VS REEFING RATIOS

1. General Discussion

Reefing data have been collected and evaluated for the following parachute types: solid circular parachutes of flat, conical, and triconical design; extended skirt parachute of 10 percent flat extended, 14.3 percent full extended, and 10 percent straight extended designs; and slotted parachutes of flat and conical ribbon, ringslot, and Ringsail designs. Data are shown as drag area ratio ξ vs reefing ratio τ in Figures 2 to 11.

Some of these figures indicate a considerable spread in reefing data. A closer examination shows, however, that the data spread is generally caused by parachutes too small in diameter to obtain valid reefing data, design characteristics such as low or high canopy porosity, and other unusual design and testing approaches.

Analysis of parachute reefing used in various recovery system applications shows a distinct difference between low rate of descent final recovery parachutes and first stage drogue and weapons retardation and aircraft deceleration parachutes. The first group of parachutes frequently referred to as low canopy loading W/C_DS parachutes, is mostly reefed to 5 to 10 percent or in the terminology of this report, to reefing ratios of 0.05 to 0.1; this includes solid flat, solid conical, and extended skirt parachutes; Ringsail parachutes with two-stage reefing frequently are reefed at ratios up to 0.25.

The second group of parachutes, with high canopy loading W/C_DS, uses reefing ratios in the range of 0.2 to 0.5; these are normally ribbon or ringslot parachutes.

Parachute reefing tests for a specific parachute, therefore, should include tests of the particular reefing ratio range used in full scale systems application. Wind tunnel reefing tests with models of 1.5 to 3.0 feet in diameter will give acceptable results in the 0.2 to 0.5 reefing ratio range. These small diameter parachutes, however, will collapse or have poor inflation characteristics at reefing ratios of less than 0.2. This means that reefing data can be obtained in wind tunnel tests on small model parachutes used in full scale application as first stage drogue or weapons and aircraft deceleration parachutes, but not on low speed final descent type parachutes. The relative stiffness of the parachute material and seams prevents small model parachutes from proper inflation at low reefing ratios.

Some of the examined test reports do not clearly define if the reefing line length is the installed length or the measured total length; often the tension (preload) is not stated under which the line length was measured. Small parachutes frequently suffer considerable shrinkage in the manufacturing process which can amount to 10 percent of the design surface area. It was not always clear if the quoted diameter was the drawing diameter or the manufactured (finished) diameter. Lack of this information can result in inaccurate data.

a. Test Methods

Data evaluated in this report were obtained: (a) in dynamic free flight tests (parachute drop tests) where parachute forces and velocities were recorded vs time by means of telemetry and photo theodolite, (b) in free flight tests with permanently reefed parachutes conducted for the purpose of obtaining reefed drag area data, and (c) in wind tunnel tests.

Dynamic free flight tests, (DFFT) in the tables and figures of this report, have the advantage that full scale parachutes are dropped reefed, then disreefed to descend fully open. This gives good reefed drag area values if reefing times of four or more seconds are used. Shorter reefing times frequently do not allow the parachute to obtain good stabilized reefed inflation. The result may be a lower drag area than that obtained in longer reefing times where the parachute had time to develop its full inflated reefed diameter. Dynamic free flight tests for full scale application generally cover reefing ratios of 0.05 to 0.1 for final descent parachutes and reefing ratios of 0.2 to 0.5 for drogue and deceleration type parachutes.

Freefall tests (SFFT) of parachutes with long reefing times or fixed reefing are the ideal approach for this purpose. Unfortunately, they are, also the most expensive means of obtaining these data.

Wind tunnel tests (WTT) are most economical, are best controlled and give results that are easily transferrable to full scale reefing if a few ground rules are observed. Test results evaluated in this report show that final descent parachutes such as solid material and Ringsail parachutes should be at least 10 to 15 feet in diameter in order to give useful reefing data. Drogue chutes, expecially ribbon and ringslot parachutes, already obtain good reefing data with parachutes of 3 to 5 feet in diameter because of the previously mentioned fact that low reefing ratios are used for final descent parachutes and large reefing ratios for drogue parachutes.

Wind tunnel tests also easily provide data over the total reefing range. This is never done in dynamic free flight tests of parachutes tested for systems application and seldom done in free fall tests of reefed parachutes due to effort and funding limitations.

b. Presentation of Test Results

All individual data points are tabulated and plotted in order to allow the reader to make his own analysis of test results. If the data point has been averaged from several tests, it is mentioned and the source of the original data is given. Tables 1 to 6 give parachute details, test information, and test results. For data that are not available in reports the source of the data is given and actual test values are tabulated.

c. Abbreviations Used

Following abbreviations are used in the tables and figures for parachute types and test methods used:

SF	-	Solid flat parachute
SC	-	Solid conical parachute
STC	-	Solid triconical parachute
ES	-	10 percent flat extended skirt parachute
FES	-	Full (14.3%) extended skirt parachute
SES	-	10 percent straight extended skirt parachute
RO	-	Flat ribbon parachute
RC	-	Conical ribbon parachute
RS	-	Ringslot parachute
RRS	-	Ringsail parachute
WTT	-	Wind tunnel tests
SFFT	-	Free flight test with permanently reefed parachutes
DFFT	-	Free flight test with temporarily reefed parachutes conducted for the purpose of obtaining load and systems data

2. Solid Circular Parachutes

Figures 2, 3, and 4 give drag area ratios vs reefing ratios for flat, conical, and triconical solid circular parachutes. Figure 2 shows good agreement of data obtained on large diameter parachutes in free flight drop test (DFFT), in free fall reefing tests (SFFT), and in wind tunnel tests (WTT). Figure 3, similar to Figure 2, also includes data on small parachute models. Several changes are obvious: drag area ratios vs reefing ratios obtained on small wind tunnel models vary widely from those obtained on large diameter parachutes. Large

parachutes can be reefed down to a ratio of 0.06 with a resultant drag area ratio of 0.016 to 0.025 and still show a tube type inflation and no flutter (see parachutes SF5, STC1, and STC2 in Figures 2 and 3). Small parachutes of 1.5 to 2 feet diameter cannot be reefed to ratios less than 0.15 to 0.2 with a resultant minimum drag area ratio of approximately 0.2 (see SF6 and SF7). The 15 foot and 8.7 foot diameter parachutes (SF3, SF4) tested in British wind tunnel tests could be reefed to approximately a 0.1 ratio.

Data on DFFT tests with large diameter parachutes were available for evaluation in the reefing range from 0.06 to 0.1 and up to 0.25 for Ringsail parachutes. Limited tests have been conducted with large parachutes and higher reefing ratios; however, these data were not available for inclusion in this report. To conduct free flight high reefing ratio tests on large parachutes for the purpose of completing curves is too expensive. The author recommends that each new parachute type that may find systems application be tested through its reefing range in a large wind tunnel. These tests provide a good understanding of reefing and good data for the required reefing ratio range.

The following comments are in order for the analysis of data obtained in free flight tests. With a short (2 seconds) reefing time, parachutes seldom obtain a steady drag area. There generally is a drag area overshoot at the beginning of the reefed stage, then a decrease followed by a gradual increase. This is less uniform on solid material than on slotted canopies. Data obtained in wind tunnel tests are by nature more uniform. Free flight tests require a number of drops in order to obtain a good average value. Errors or inaccuracies in measured values of speed and altitude obtained by phototheodolite, in loads obtained by strain gages and telemetry, and in atmospheric conditions can result in notable variations.

Figure 4 shows that few good data are available in the reefing ratio range below 8 percent. Attempts by the author to obtain useful reefing data on the G-11A and G-12 cargo parachutes were unsuccessful. Both parachutes are reefed to ratios below 0.06; however, data were never recorded in sufficient detail to permit the analysis required for this report.

a. Discussion of Individual Parachute Tests

Table 1 lists data on solid flat parachutes tested, on test conditions, on drag area ratios vs reefing ratios, and the source of these data.

Parachute Series SF1; Reference 8:

The Recovery and Crew Station Branch of the USAF Flight Dynamics Laboratory in 1964 conducted a series of tests with reefed solid flat circular and extended skirt parachutes at the DOD El Centro Parachute Test Facility.

The solid flat parachute tested was a standard 28 foot diameter man-carrying type, reefed for 4 seconds, using a 550 pound reefing line. The parachutes were dropped at speeds of 130 knots from a C-130 aircraft flying at 6,000 feet altitude. Velocity, loads, altitude, trajectory angle, atmospheric density, temperature, and humidity were carefully measured; the author was furnished the test records. The quick opening 28 foot diameter solid flat parachute produced a (C_dS) overshoot in the beginning of the reefed phase and increased the (C_dS) sooner than would be expected from the 4 seconds reefing time. This may be caused by the smoothing technique used in the determination of phototheodolite velocity data. A careful analysis conducted during the Apollo parachute test program determined that this smoothing technique could result in recorded dynamic pressure errors of as much as 10 percent at the start and the end of the reefing period; this had a definite effect on the calculated C_dS values. A 2-second track in the middle of the 4-second reefing time, therefore was selected for analysis of these tests with readouts available for every one-hundreth of a second. Despite considerable fluctuation of the measured C_dS vs time, the average values for the 2-second period were relatively uniform as shown in Table 1 and Figures 2 and 3.

Parachute Series SF2; Reference 9:

The author had access to the results to unpublished reefing tests conducted in 1953 at the El Centro Parachute Test Facility with permanently reefed 24 foot diameter T-10 reserve parachutes, see SF2 in Table 1. The rate of descent in these tests was obtained with the drop line method and the drag area calculated from the known rate of descent, parachute dimensions, drop weight, and atmospheric data. Tests were performed with: (a) the parachute tied together at the skirt; (b) the shortest possible reefing line; and (c) with reefing ratios D_{R1}/D_{R_o} of 0.4, 0.6, 0.8; and full open. The parachute tied closed at the skirt would not inflate but descended stable with the canopy waving in a snake-like fashion; this canopy had a drag area ratio of approximately 0.015.

Tying the shortest possible line through the reefing rings produced a tube-like inflation with no flutter and a drag area ratio of approximately 0.025. These results agree well with data obtained on a 28 foot diameter parachute (SF5) tested reefed in the Ames 40/80 foot wind tunnel which had a minimum drag area ratio of 0.025.[7]

Parachute Series SF3 and SF4; Reference 2:

In 1960, in Farnborough, England, M.H.L. Waters and Associates conducted wind tunnel tests on parachute reefing. The parachutes tested included numerous British designs and solid flat and solid conical models of 8.7 feet and 15 feet diameter. These tests are of particular interest because they include tests with parachutes of three different suspension line lengths, L_S/D_O = 1.33, 1.0, and 0.67,

variation in material porosity, and in number of suspension lines for the same parachute diameter. Suspension lines longer than $L_S/D_O = 1.0$ are used frequently for drogue chutes and cluster main parachutes substituting required riser length with longer parachute suspension lines which result in an up to 10 percent increase in drag without an increase in parachute weight.

The British authors use as reference for the calculation of reefing and drag area ratios the values obtained for the full open parachute with the line ratio $L_S/D_O = 1.33$. This report uses the data obtained with the full open parachute with a line ratio L_S/D_O of 1.0 as reference. For most applications, parachutes with this line ratio will be the starting point for systems design. The difference in drag area ratio for the same reefing ratio due to line length is neglectable at small reefing ratios, see Figure 3. For large reefing ratios, an increase in drag area occurs for the parachutes with long suspension lines and a decrease for the parachutes with short suspension lines.

Tests included a 15 foot solid flat canopy with 1/3 of the standard porosity. This parachute had a higher drag area ratio at low reefing ratios than other solid flat parachutes, most likely due to a larger inflated reefed diameter at low reefing ratios.

Parachute Series SF5; Reference 7:

Tests were conducted in 1963 with Apollo parachutes in the NASA Ames Research Center 40 by 80 foot wind tunnel. The prime purpose was to investigate inflation characteristics of various Ringsail parachute designs. Included in these tests were a 28 foot diameter solid flat circular, a 24 foot diameter solid circular conical, and a 32 foot diameter solid hemispherical parachute.[5, 7] Tests were conducted at reefing ratios of 0.08, 0.13, 0.18 at dynamic pressures of 5, 10, and 15 psf. Results obtained with the 28 foot diameter solid circular flat parachute are listed under SF5 in Table 1 and Figures 2, 3, and 4. The results of these wind tunnel tests agree very well with reefing data obtained in free flight tests.

Parachute Series SF6 and SF7; References 10 and 11:

In 1963 and 1964, the USAF, at Wright-Patterson AFB, conducted two parachute wind tunnel programs of (a) parachute clusters, and (b) the investigation of drag and stability of various parachute types[10, 11] Both programs included tests with reefed parachutes covering the reefing range from minimum possible to full open. These tests with parachutes of 1.5 and 2 0 feet in diameter gave good results in the prime areas of investigation, namely, parachute clustering, static stability, and full open performance. The data on parachute reefing were, however, subject to the previously mentioned limitations, that of size. The relatively high stiffness of the small parachutes makes it impossible to reef to low ratios and changes reefing data in the medium reefing range.

Parachute Series SC1; Reference 7:

Today solid conical parachute types are used in preference to solid flat parachutes as final descent parachutes. Only one test series could be found, however, that provided reliable reefing information on straight solid conical parachutes. Tests with a 24 foot diameter conical parachute were part of the Apollo parachute wind tunnel test program in the NASA Ames 40 by 80 foot wind tunnel. The drag area ratios, listed in Table 2 and shown in Figures 2 and 4, appear to be slightly higher than those obtained on solid flat parachutes. Several agencies and individuals contacted expressed the opinion that little difference seems to exist between the reefing of solid circular flat and solid circular conical parachutes.

Parachute Series STC1 and STC2; Reference 13:

The Pioneer Parachute Company has developed a series of "Triconical" solid circular parachutes. Data were provided by J. Reuther from Pioneer on free flight drop tests of reefed 76 foot diameter and reefed 100 foot diameter parachutes. Numerous tests were conducted with both parachutes, but with one reefing ratio only. The 100 foot diameter parachute was dropped with test weights of 2200 pounds and 3600 pounds, resulting in canopy loadings W/S of 0.255 and 0.458 psf, and rates of descent of 17 and 21 ft/sec. Drag areas of 150 ft^2 and 130 ft^2, respectively, were obtained for the same reefing ratio with the two canopy loadings, see Table 2 and Figures 2, 3, and 4. It appears that the higher canopy loading produced a slightly smaller inflated reefed diameter.

3. Extended Skirt Parachutes:

Reefing data have been obtained on three types of extended skirt parachutes: on a 10 percent flat extended skirt design (ES), on a 10 percent straight extended skirt design (SES), and on a 14.3 percent full extended skirt design (FES). Eight different groups of reefing tests were evaluated. Four of these test series are free flight tests (DFFT) on parachutes from 28 feet to 78 feet in diameter; the remaining four are wind tunnel tests using 1.5 foot diameter and 1.9 foot diameter parachutes. The results are similar to those obtained with solid circular parachutes. All free flight tests use reefing ratios of 0.05 to 0.10 with corresponding drag area ratios of 0.02 to 0.05.

Test series ESI was conducted as a research project using a reefing ratio of 0.3 similar to the solid circular SF1 test series.

The small diameter wind tunnel models behaved similar to the small solid flat circular models. Reefing ratios below 0.17 could not be obtained due to collapse of the relatively stiff parachute canopy.

There is no observable difference in the drag area ratio vs reefing ratio among the three types of extended skirt parachutes. A detailed examination of Reference 12 shows that the 34.5 ft diameter 10 percent extended skirt parachute developed as descent parachute for the B-70 encapsulated seat, had a slightly higher drag area for the same reefing ratio. As the report points out, however, this parachute was designed for fast inflation, a characteristic that generally results in high drag area ratios.

A direct comparison of solid flat and extended skirt parachutes (See Figure 11) shows that for the same reefing ratios both have practically identical drag area ratios.

Details of all tested parachutes including references are listed in Table 3. Resultant reefing and drag area ratios are shown in Figure 5.

4. Ringslot Parachutes

Few data are available on reefed ringslot parachutes. A 17.7 ft diameter reefed ringslot parachute was developed by Northrop in 1964 as final descent parachute for a reentry body with a water entry velocity of 50 ft/sec. This parachute, reefed in one step, was tested at speeds up to 360 knots. (14) The data are recorded in Table 4 as RS1. The two USAF wind tunnel test programs for the investigation of cluster parachutes and the static stability characteristics of parachutes include reefed ringslot parachutes. (10, 11)

The results of the free flight parachute tests and tests with small wind tunnel models are listed in Table 4 and in Figure 6. The wind tunnel test data on the small parachutes RS2 and RS3 are still somewhat higher than the results of the freeflight tests with the larger parachutes. The difference is not nearly as pronounced however, as on solid circular and extended skirt parachutes.

An interesting reefing program was conducted in 1954 by the USAF 6511th Test Group in El Centro, California with a 34 ft diameter ringslot parachute developed for a 500 lb. U.S. Marine aerial resupply container. It was observed that the parachute, at test speeds up to 500 knots, would open into the reefed position by stepwise inflation of the concentric rings forming the canopy; the opening process also appeared to be velocity sensitive. The reefing line was then eliminated and a large circumferential slot introduced into the canopy located at the leading edge of the inflated reefed canopy area. As result of this change, the parachute would open but stop inflating as soon as it reached the large slot. The canopy inflated fully, independent of drop speed, as soon as the velocity decreased to approximately 100 knots.

All tests were conducted with parachutes made by the same manufacturer from the same lot of canopy material with the test results reasonably uniform. Whether this phenomenon can be utilized in operational application is uncertain if one considers the allowable material porosity variation and tolerances in the manufacture of parachutes. A similar behavior, the step by step opening of individual rings, was later experienced on the large Ringsail parachutes used for space vehicle recovery.

5. Ringsail Parachutes

The determination of the reefed drag area of Ringsail parachutes is more complex than for other parachutes because Ringsail parachutes open in steps and grow during reefed opening. The reefed 88 foot diameter main parachutes for the Apollo I command module would open quickly to the fourth ring, thereafter a slow stepwise inflation would occur until the growth stopped with the seventh ring semi-inflated. This process took several seconds. Growth in the reefed drag area is a distinct advantage for single main parachutes as used for the Mercury and Gemini space capsules. It created a major problem on the cluster of three Apollo main parachutes. One or two of the parachutes would be in a "lead" position at reefed inflation, grow faster, and obtain an earlier full inflation after disreef. This led to overload and damage in the lead parachute(s). An extensive wind tunnel test program was conducted in the NASA Ames 40 by 80 foot wind tunnel using full scale, one-half scale, and one-third scale parachutes. The primary purpose of these tests was to investigate the Ringsail parachute inflation process aimed at obtaining a more uniform cluster opening. A secondary objective was to obtain data on the reefing of Ringsail parachutes.[5, 7] The full scale 88 foot diameter Apollo I parachute and the one-half scale version were only tested in the reefed configuration. The small scale, 28 foot diameter Ringsail parachute was tested reefed and full open.

Modifying the 88 foot diameter Apollo I parachute with a circumferential slot equal in width to 75 percent of the fifth ring greatly improved uniform inflation of the three parachutes. The slot stopped the reefed inflation at the fifth ring and allowed the lag parachute(s) to catch up before disreefing occurred.

All reefed Ringsail parachute data are listed in Table 3 and shown in Figures 7 and 8.

Configuration RRSI shows the drag area vs reefing ratio for the two reefing stages of the final 85 foot diameter Apollo main parachutes. Even the parachute modified with the slot at the fifth ring had a modest amount of growth; this can be seen from the difference between the initial reefed drag area and the drag area at disreef in both the first and second reefing stages, see columns (F) and (D) in Table 5.

Wind tunnel tests with reefed Ringsail parachutes will give high drag area values because the parachutes have obtained their reefed full inflated position. This occurs seldom in free flight tests due to limited reefing times.

Data were provided by the USAF/ASD B-1 SPO on reefing the cluster of three each 70 foot diameter Ringsail main parachutes for the B-1 crew module.[15] These tests, shown as RRS4, confirm that data obtained in free flight tests are somewhat lower than data obtained in wind tunnel tests for the aforementioned growth reasons.

The data in Figure 7 show the high values for the wind tunnel test models, RRS2, RRS3, and RRS6, and the somewhat lower values for the free flight tests RRS1, RRS4, and RRS5.

Figure 8 compares data on Apollo parachutes with skirt reefing and mid-gore reefing. The only direct comparisons were obtained in the Ames wind tunnel tests with a single Apollo I parachute of 88 feet diameter tested with both types of reefing. Comparing the 85 foot diameter final Apollo II parachutes with mid-gore reefing with the 70 foot diameter B-1 parachutes with skirt reefing confirms the higher drag area ratios for the Apollo parachutes with mid-gore reefing. Additional Ringsail reefing data can be found in the Ringsail Parachute Design report.[4]

6. Ribbon Parachutes

More reefing data are available on ribbon parachutes than on any other parachute type. Ribbon parachutes are used primarily for three applications: first stage drogue parachutes for missile and drone recovery, weapons retardation parachutes, and aircraft deceleration parachutes. All three applications require a rather precise knowledge of the aerodynamic characteristics of the decelerator. Drogue chutes are relatively small and can easily be tested in the wind tunnel. The initial application to weapons made the acquisition of good reefing data mandatory. In addition, most of these projects were handled by government agencies, which made it easier to plan and execute aerial as well as wind tunnel tests. Data covering the total reefing ratio range were obtained with large and small ribbon parachutes in wind tunnel, free flight, and aircraft tow tests.

The investigated parachutes are listed in Table 6. Drag area ratios vs reefing ratios are shown in Figures 9 and 10. Appendices A and B provide unpublished data on two test programs on reefing of ribbon parachutes.

A large series of reefing tests were conducted at El Centro from 1952 to 1954. The results of these special tests are plotted separately in Figure 10 so as not to make summary Figure 9 illegible. All data show relatively good agreement.

Individual Test Results

Parachute Series RC1; Appendix A:

The US Army USD-5 reconnaissance drone used a 13.4 foot diameter 25-degree conical ribbon parachute as first stage drogue chute during the R&D phase. The USAF 6511th Test Group at El Centro conducted a series of reefing tests towing this parachute behind a C-130 aircraft. Since the parachute was tested in six reefing steps from 0.075 reefing ratio to full open with the airspeed varying from 120 knots to 200 knots, the aircraft tow speed had to be reduced with increasing parachute drag area in order to maintain good C-130 flying conditions. Most reefing ratios were tested over the increasing and the decreasing speed range. The absolute values were approximately 5 percent low due to the wake effect behind the aircraft; however, reefing and drag area ratios related to the full open towed parachute are considered reliable. Details of the parachute, the test procedure, and test results are contained in Appendix A of this report.(16)

Parachute Series RO2 and RO2A; Reference 17:

A heavy-duty, 64 foot diameter ribbon parachute with 1000 pound horizontal ribbons, 84 gores, and 6000 pound suspension lines was tested at El Centro in 1953 in reefed free-fall tests. The rate of descent and the resultant drag area were determined by the drop line method measuring the rate of descent for the last 300 feet. This seemingly crude method, however, yielded good results. The parachute was tested in two versions. The original porosity of close to 20 percent (RO2 A) resulted in a sloppy, slow tube type inflation with low drag areas. A 28 foot standard man-carrying canopy then was inserted in the vent area which reduced the porosity to 14.5 percent. The resultant bulb-like inflation caused high drag area ratios as can be seen in Figure 9. Data for this parachute were taken from Reference 17 and original test data in the possession of the author.

Parachute Series RO3; Reference 18:

A large test program with reefed ribbon parachutes was conducted in 1952 at the El Centro Parachute Test Facility. These tests cover a complete series of reefing tests using 12, 16, 20, and 40 foot diameter flat ribbon parachutes of heavy construction (500 and 1000 pound horizontal ribbons and 6000 pound suspension lines). Reference 18 summarizes these tests; additional data were obtained from the files of the author. Each individual test is tabulated in Table 6 and plotted in Figure 10.

Parachute Series RO4; Reference 19:

In 1950, a heavy design 3.0 foot diameter flat ribbon parachute was tested in the Wright Field Massie Memorial 20 foot wind tunnel. These tests were part of a program to develop a stabilization and deceleration parachute for the pilot escape nose section of the X-2

research aircraft. The parachute was tested with and without forebody at reefing ratios from 0.208 to full open and speeds from 100 mph to 250 mph. The data of these tests, plotted in Figure 9, agree well with other test results. Appendix B of this report gives details of this program.

Parachute Series RC5, RC6, and RC7; Reference 20-21:

The Sandia Laboratories in Albuquerque have tested reefed ribbon parachutes over a wide range of diameters, test vehicles, and speeds. Included in this report are reefing tests with 16, 40, and 76 foot diameter heavy-duty ribbon parachutes. The data were obtained in free-flight tests with velocities and position measured by Contraves phototheodolite cameras. The referenced data are not tabulated but plotted directly in Figure 9 under RC5, RC6, and RC7. The data for the 16 and 40 foot diameter parachutes agree well with other test results. The reefed drag area of the 76 foot diameter parachute is low over the total tested range. No explanation could be found for this anomaly, except that the porosity of this parachute was relatively high. All parachutes were of 20 degree conical design. It should also be noted that Sandia Labs does not use the nominal diameter D_O, but the diameter of the base of the canopy cone as reference diameter; this establishes the relationship $D_{Sandia} = D_O/1.033$.

Parachute Series RO8 and RC9; Reference 11:

A 1.5 foot diameter flat and a 1.5 foot diameter 20 degree conical ribbon parachute were included in the test series in the Wright Field 1 meter wind tunnel.(11) The test range covered reefing ratios from 0.2 to full open. Table 6, sheet 6, and Figure 9 show that the reefed drag areas obtained in this reefing ratio range agree well with data obtained on large parachutes in free-flight tests.

Parachute Series RO10; Reference 10:

A single 1.9 foot diameter flat ribbon parachute was included in the investigation of clustered parachutes conducted in the Wright Field wind tunnel. The results are shown in Table 6, sheet 6, and in Figure 9. Again, as in the previous test series, there is good agreement with test data obtained on large parachutes.

Evaluation of the reefed 16.5 foot diameter conical ribbon drogue parachute for the Apollo II Command Module shows good agreement with data listed so far; no detailed data presentation was therefore made.(22)

7. Summary

Average drag area ratio vs reefing ratio data for solid circular, extended skirt, ringslot, Ringsail, and ribbon parachutes have been calculated and plotted in Figure 11. The average data for the solid

circular and extended skirt parachutes are almost identical considering the normal variations in test results. One should also remember that reefing ratios above 0.1 are seldom used on final recovery parachutes that descend with velocities in the 15 to 35 ft/sec range.

The reefed drag area values for slotted parachutes are notably higher than for solid material parachutes. This can not be related to inflated diameter. In fact, Reference 11 shows that ribbon, ringslot, and Ringsail parachutes have smaller inflated diameters for the same reefing ratio than solid material and extended skirt parachutes. A possible explanation appeared in tests with reefed parachutes in the Apollo NASA Ames wind tunnel. These tests showed a strong outward directed turbulent air flow through the slots of Ringsail parachutes. This factor could cause the turbulent area around slotted canopies to be relatively larger than the turbulent area of solid material parachutes.

The data on ringslot parachutes at low reefing ratios are based on only one series of free-flight tests. Wind tunnel tests on small parachutes indicate the average values to be similar to those of ribbon parachutes.

The average drag area values for Ringsail parachutes have only comparison value due to the variation of reefed drag area with time. It can be stated however, that the drag area ratio values for the same reefing ratio are close to those shown for ribbon parachutes which means the Ringsail parachute behaves similarly to the other slotted parachute types.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

1. A wealth of reefing data is available on solid flat, solid conical, extended skirt, and ribbon parachutes. Any additional general reefing tests on parachutes of this type are considered of little value by the author.

2. Few data are available on ringslot parachutes in the low reefing ratio range and on Ringsail parachutes in the higher reefing ratio range.

3. Final descent parachutes of solid flat, solid conical and extended skirt designs are normally reefed to ratios of .05 to .10 and in special cases up to .25. Tests with small diameter parachutes of these types do not provide useful data at these low reefing ratios due to poor reefed inflation. Reefing tests with final descent parachutes should be conducted with parachutes with a minimum size of 10 to 15 feet in diameter.

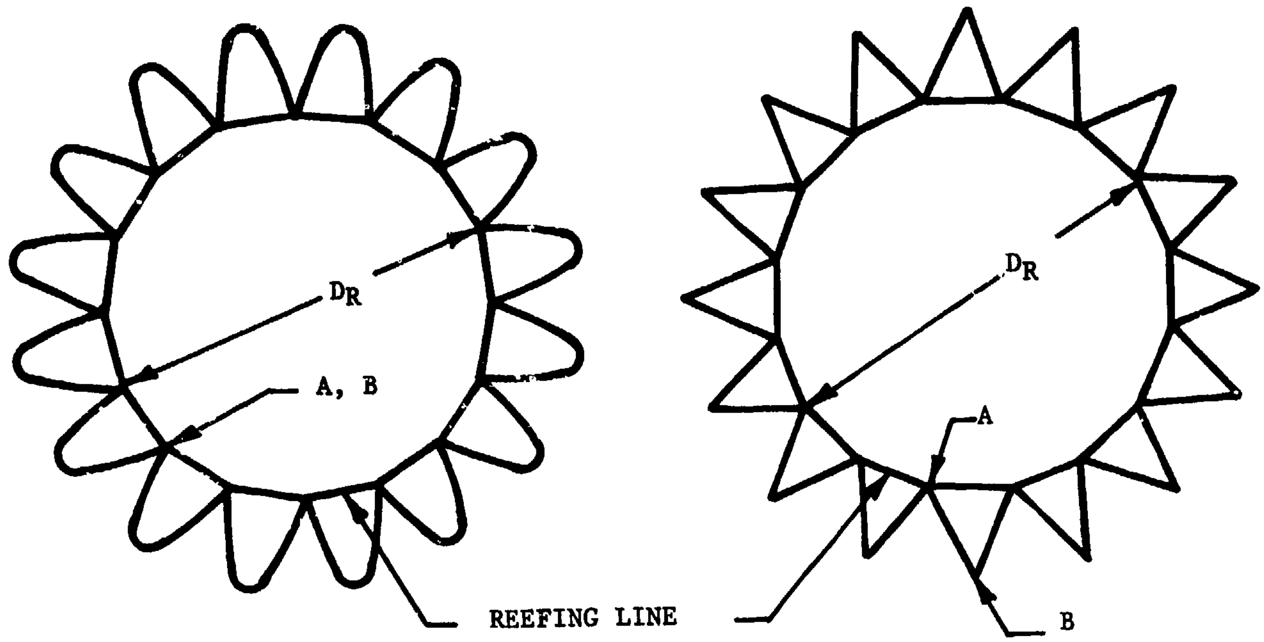
4. High canopy loading drogue or deceleration parachutes, such as ribbon and ringslot parachutes, use reefing ratios of 0.2 to 0.5. This is a reefing range where parachutes with only 2 to 3 feet in diameter already provide useful data.

5. Differences in suspension line length, number of gores, and canopy porosity cause variations in the drag area ratio for the same reefing ratio. These variations are generally small for low reefing ratios but increase with larger reefing ratios.

6. Drag area data for the same reefing ratio may vary up to 10 percent from the average value. If reefing data with a higher accuracy are required, reefing tests must be conducted with that particular parachute for fine-tunning of the reefing system.

7. It is advisable to conduct reefing tests in a large wind tunnel with any new parachute design that may find wide application. Parachute size and wind tunnel required depend on the utilization of this new design as final descent parachute or drogue parachute.

8. Besides drag area vs reefing ratio data, loads in the reefing line are required for proper selection of the reefing system. It is recommended that this investigation be extended to an analysis of all data obtained on reefing line forces.



(a) SKIRT REEFING

(b) MID-GORE REEFING

A - REEFING RING

B - SUSPENSION LINE ATTACHMENT POINT

Figure 1. Comparison of Skirt Reefing and Mid-Gore Reefing

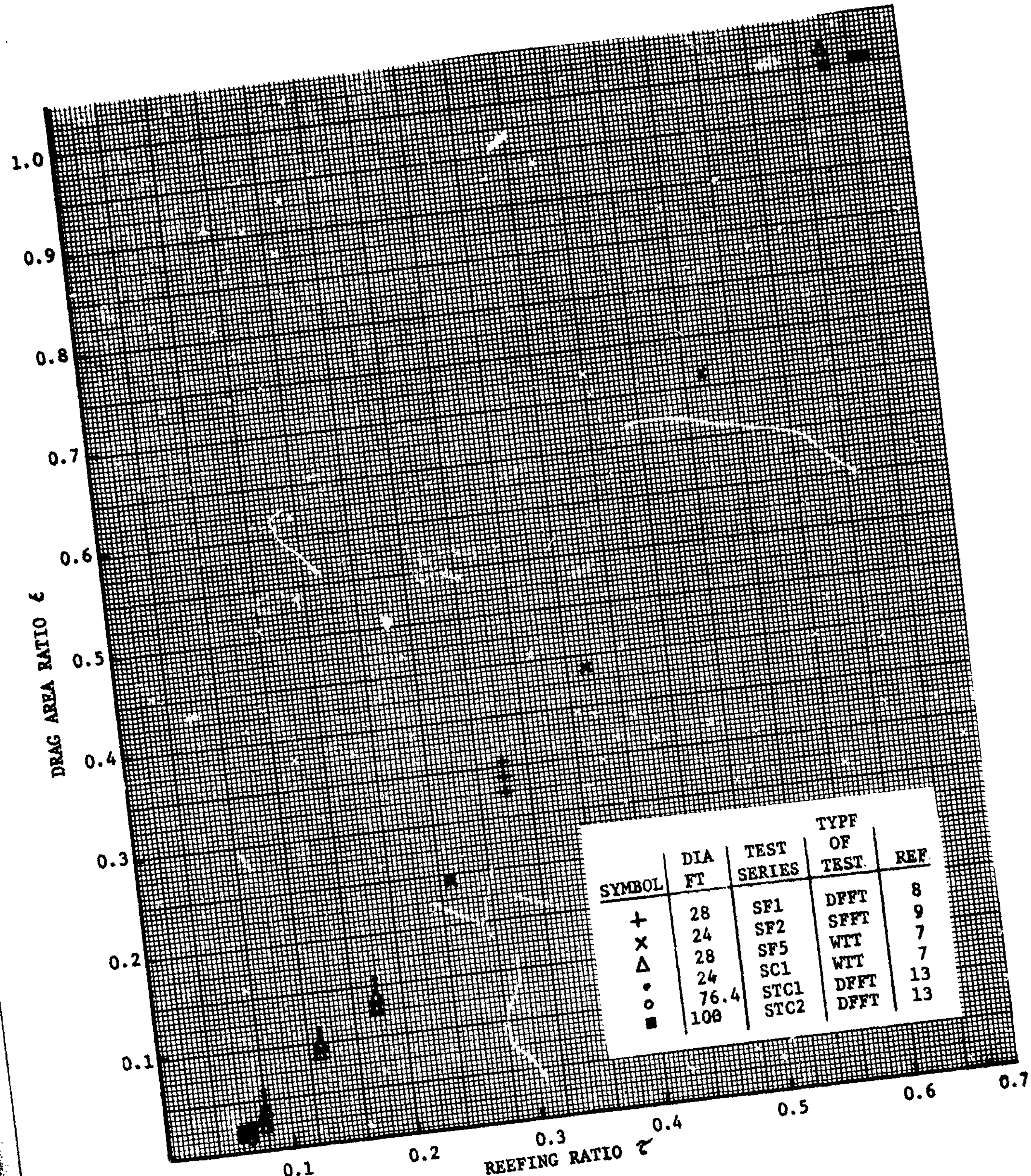


Figure 2. Drag Area Ratio ε vs Reefing Ratio τ for Solid Circular Flat, Conical, and Triconical Parachutes Larger than 15 Feet in Diameter D_o

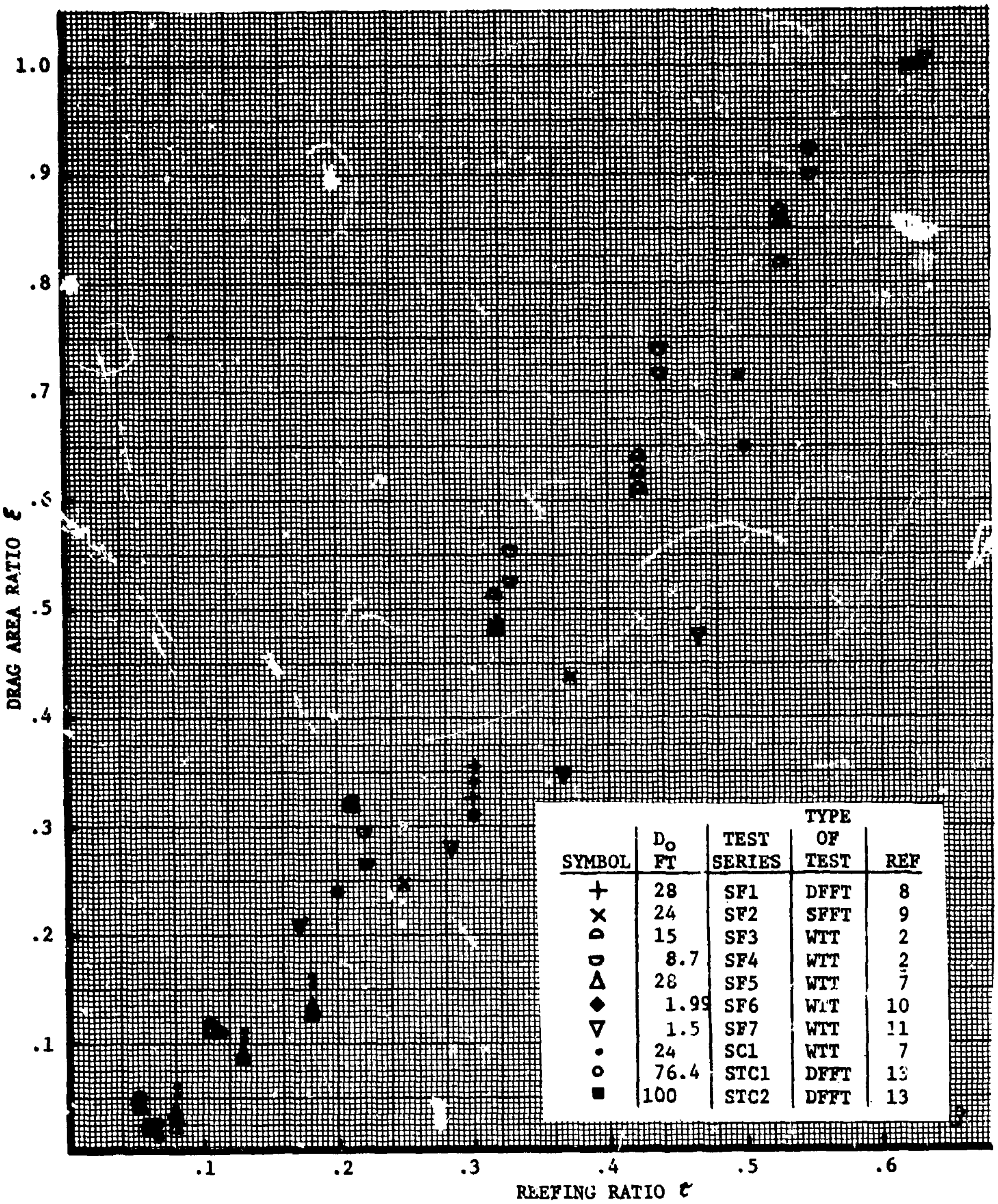


Figure 3. Drag Area Ratio ε vs Reefing Ratio τ for All Solid Circular Flat, Conical, and Triconical Parachutes

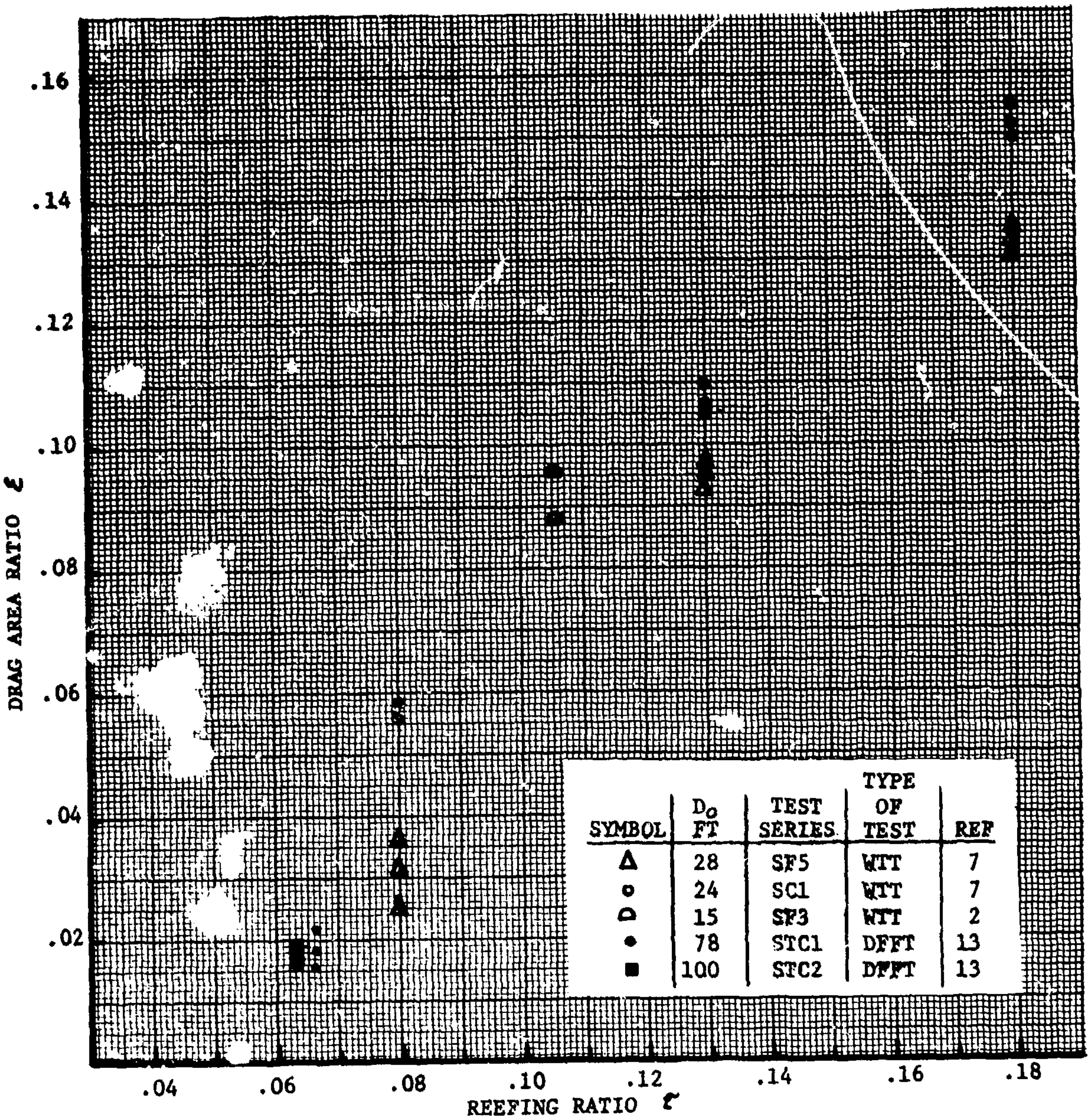


Figure 4. Drag Area Ratio $\mathscr{E}$ of Large Solid Circular Parachutes for Reefing Ratios τ = 0 to 0.18

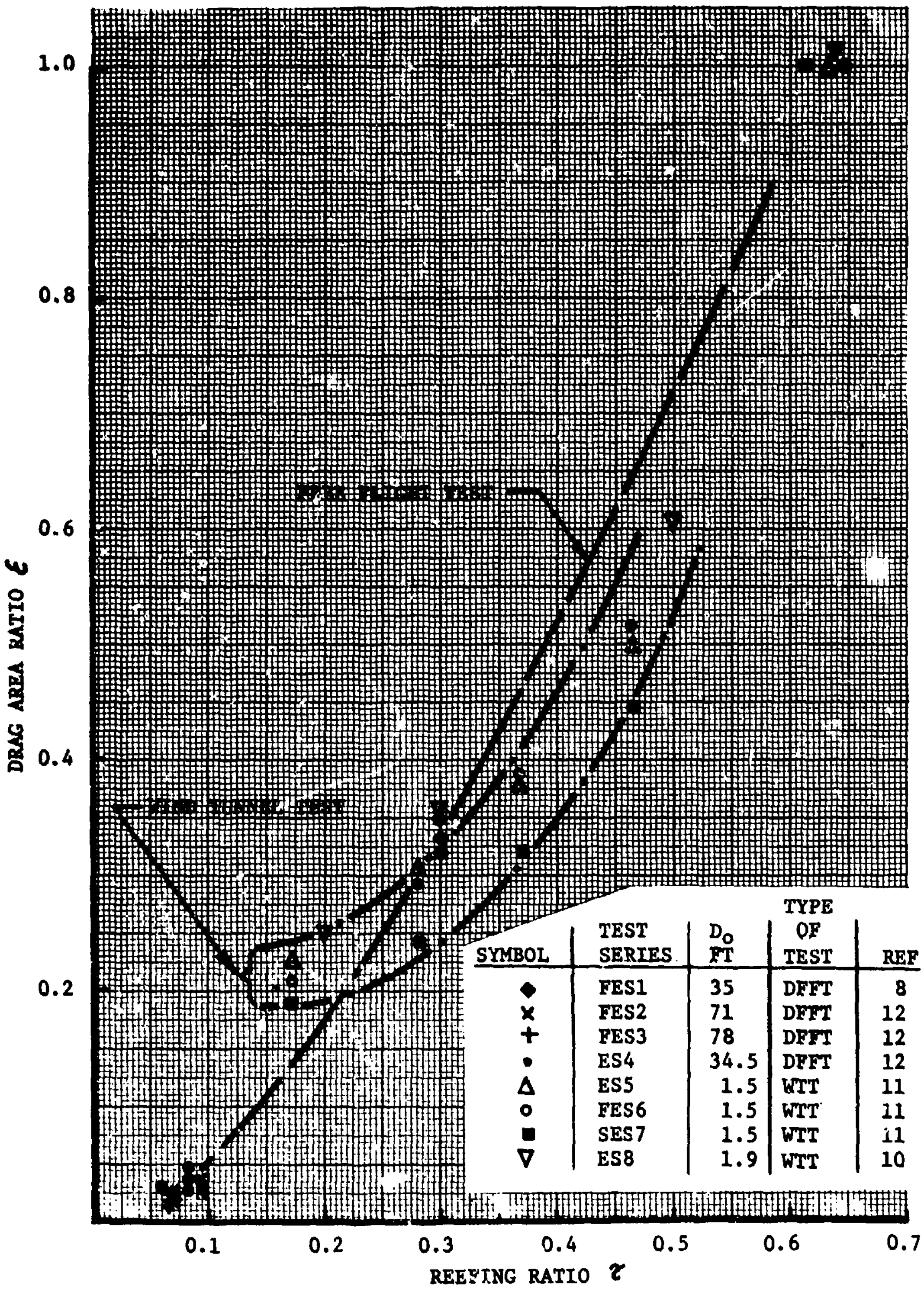


Figure 5. Drag Area Ratio ε vs Reefing Ratio τ for Extended Skirt Parachutes

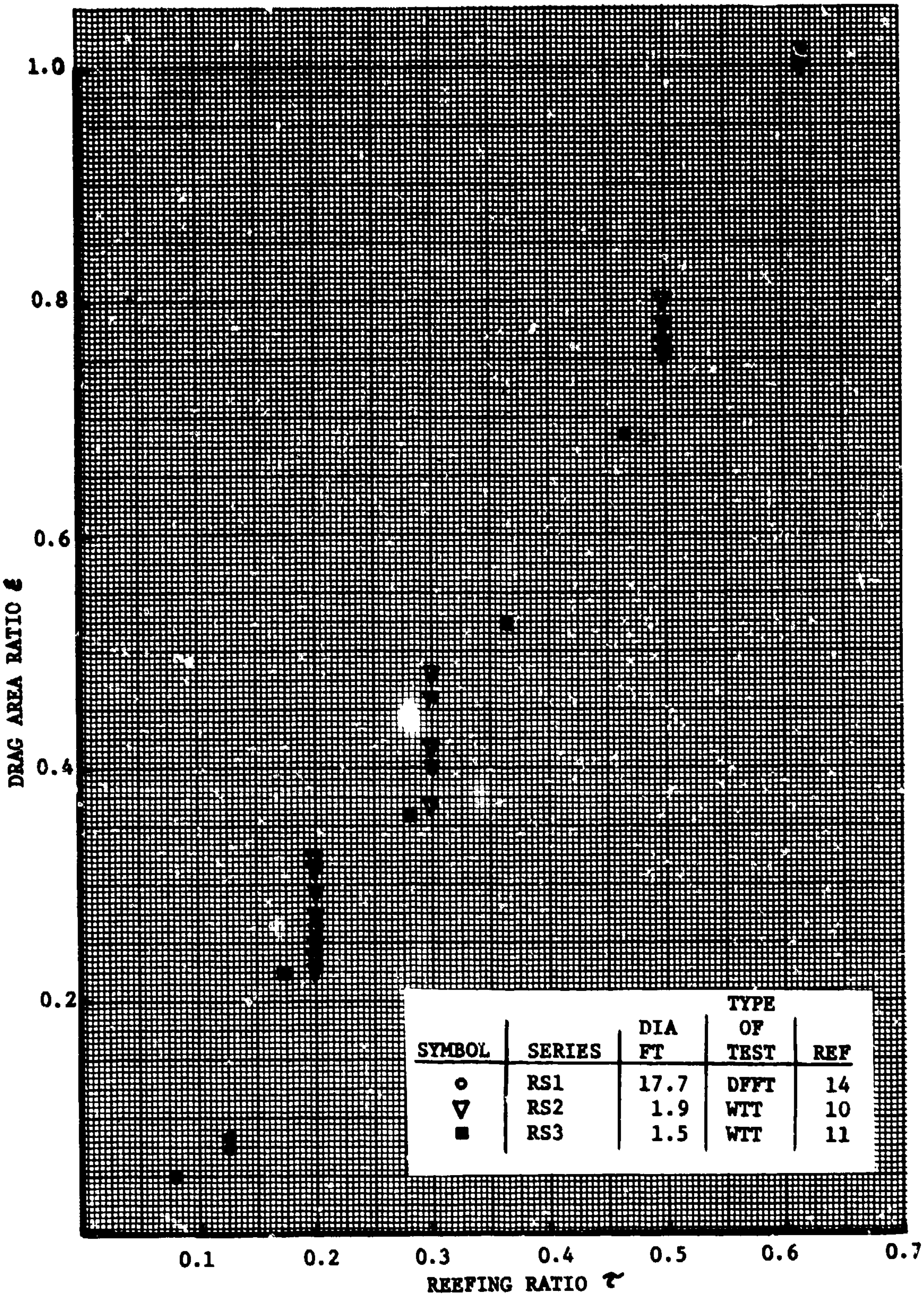


Figure 6. Drag Area Ratio ε vs Reefing Ratio τ
for Ringslot Parachutes

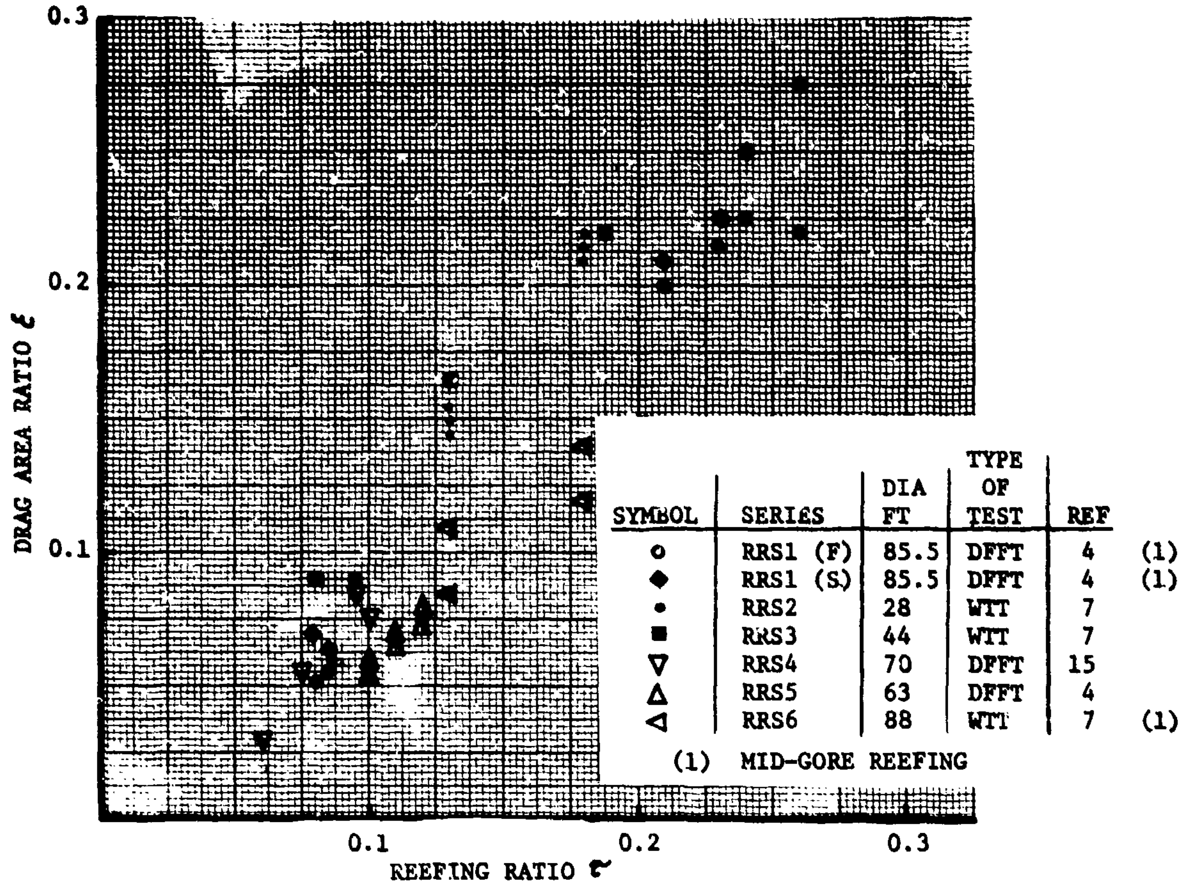


Figure 7. Drag Area Ratio ε vs Reefing Ratio τ for Ringsail Parachutes

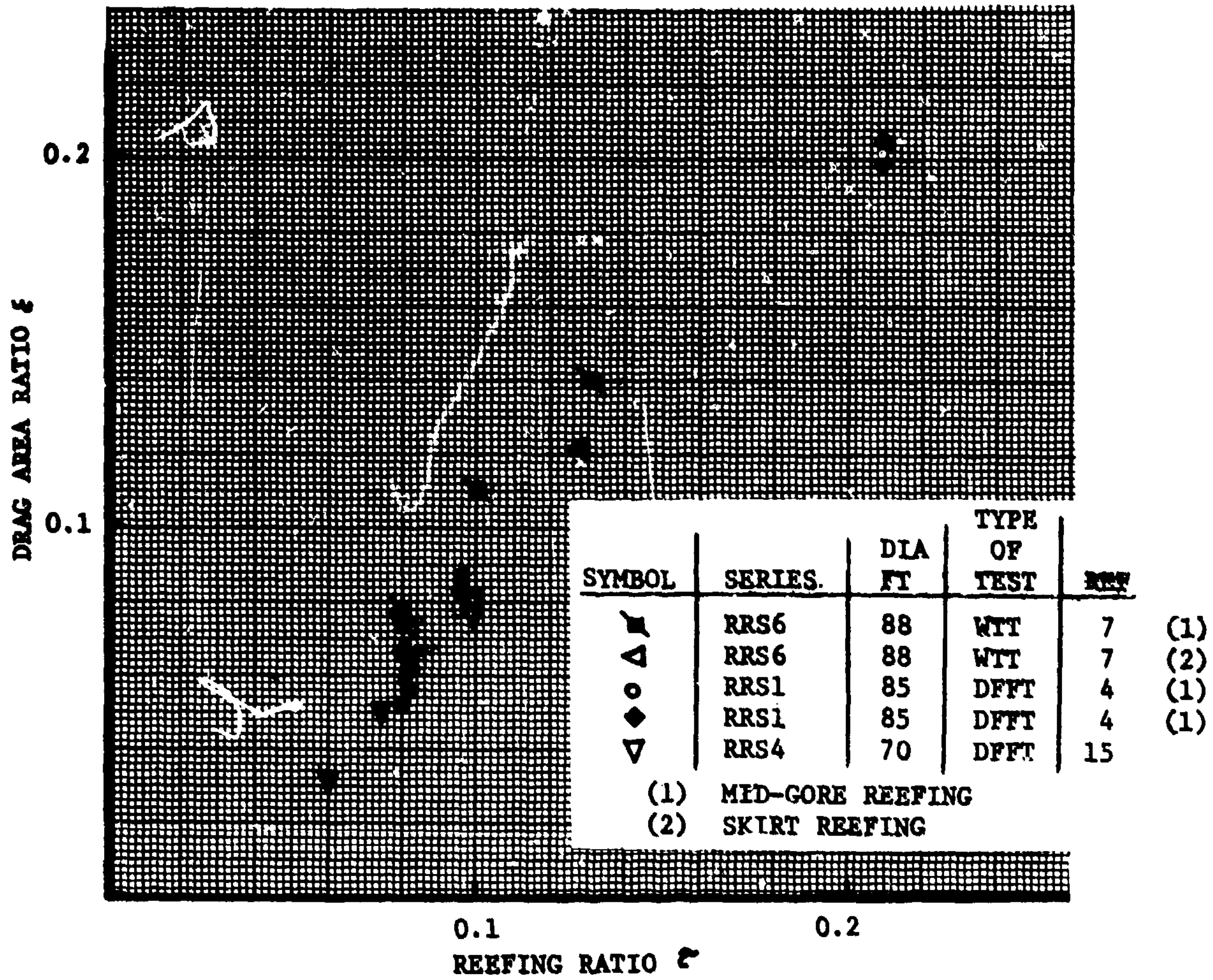


Figure 8. Comparison of Skirt Reefing and Mid-Gore Reefing of Ringsail Parachutes

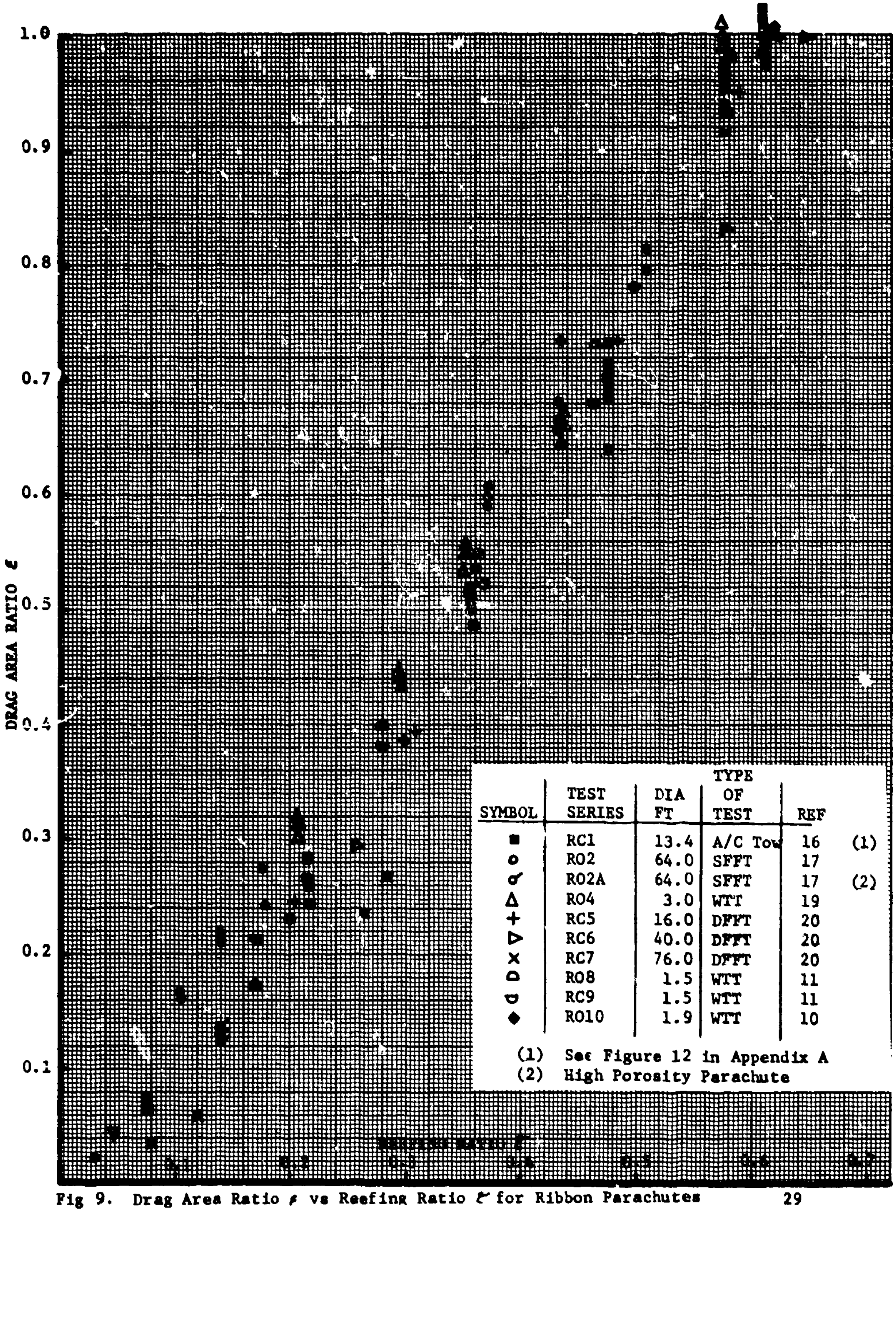


Fig 9. Drag Area Ratio ϕ vs Reefing Ratio τ for Ribbon Parachutes

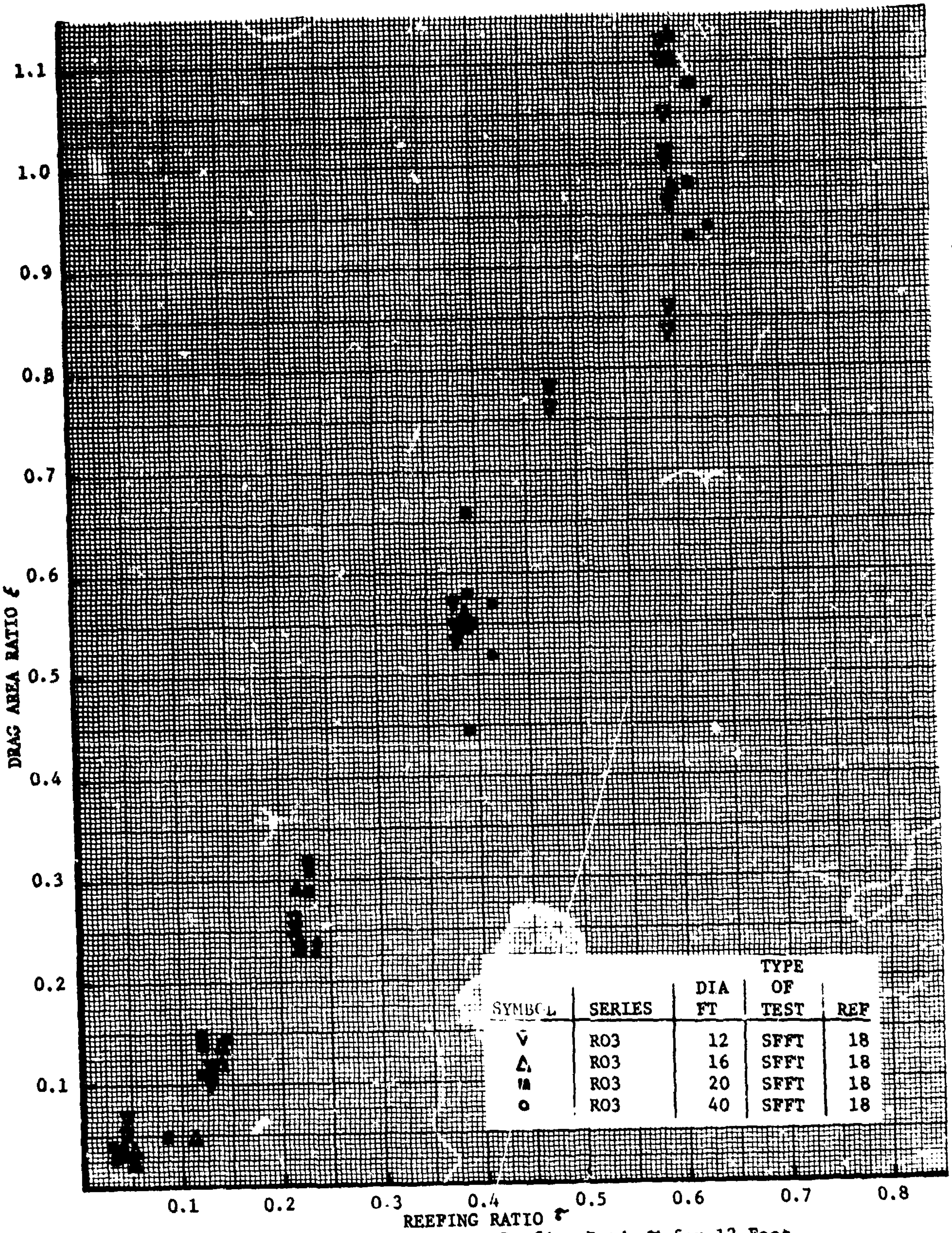


Figure 10. Drag Area Ratio ε vs Reefing Ratio τ for 12 Foot to 40 Foot Diameter Ribbon Parachutes

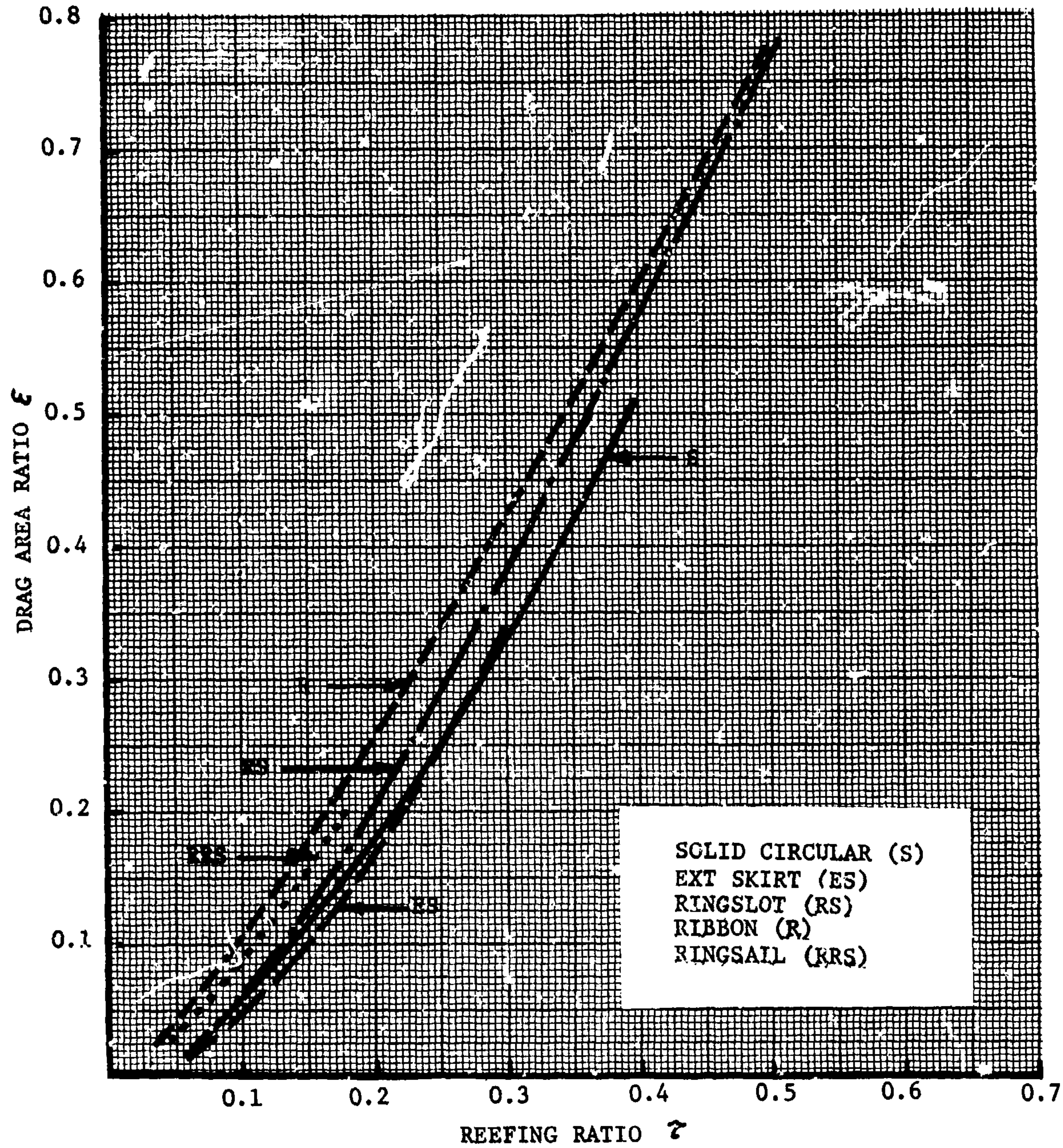


Figure 11. Drag Area Ratio ε vs Reefing Ratio τ for Solid Circular, Extended Skirt, Ringslot, Ringsail, and Ribbon Parachutes - Summary Chart

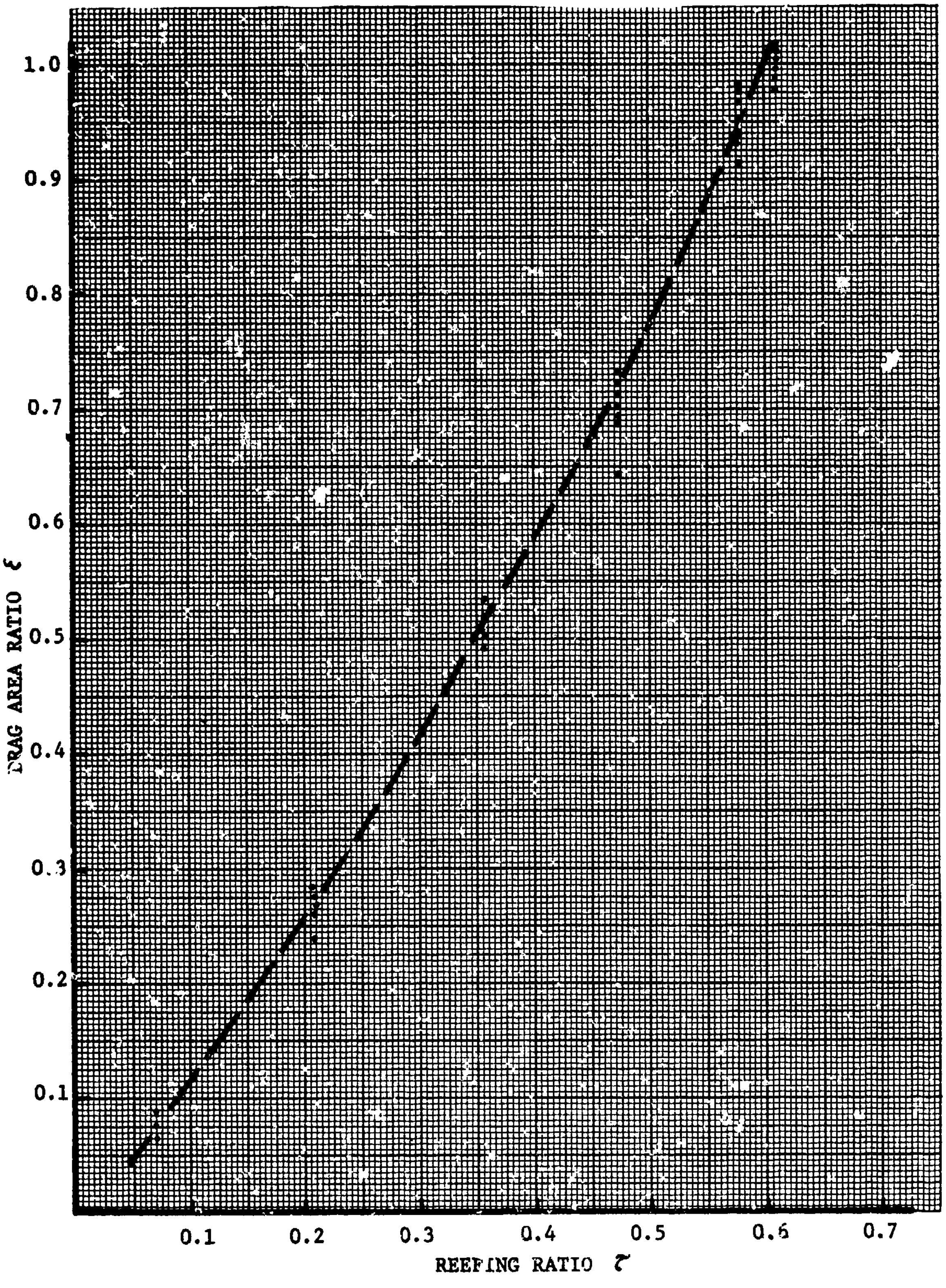


Figure 12. Drag Area Ratio ϵ vs Reefing Ratio τ for 13.4 Foot Diameter Conical Ribbon

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$		Ref	Comments
SF 1	1964	El Centro	DFFT	126 Kn	28	28	4	0.301	0.354		8	
									0.340			
									0.326			
SF 2	1953	El Centro..	SFFT	40 fps	24	24		.248	0.245		9	Average of 3 tests each
								.372	0.435			
								.496	0.715			
								.62(1)	1.0			
SF 3	1960	Farnborough U.K.	WTT	60 fps	15	48			(1)	(2)	2	(1) Original measurement
						L_s = 240"		F.O.	1.0	1.11		
						L_s/D_o = 1.33		.637	.944	1.05		(2) Corrected for L_s/D_o = 1.0
								.53	.775	.857		
								.424	.577	.640		F.O. = full open
								.318	.463	.514		
								.212	.291	.323		
								.106	.101	.112		
								.053	.045	.050		
SF 3	1960	Farnborough U.K.	WTT	60 fps	15	48			(1)	(2)		
						L_s = 180"		F.O.	.902	1.0		
						L_s/D_o = 1.0		.53	.780	.864		
								.424	.566	.627		

TABLE 1 SOLID FLAT CIRCULAR PARACHUTES SHEET 1

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D.S)_R}{(C_D.S)_o}$		Ref	Comments
SF 3	1960	Farnborough	WTT	60 fps	15	48	–		(1)	(2)	2	(1) Original
Cont		U. K.				L_s =		.318	.439	.486		measurement
from						180"		.212	.286	.317		
Sheet 1						L_s/D_o		.106	.106	.117		(2) Corrected for
						= 1.0		.053	.040	.044		L_s/D_o = 1.0
SF 3	1960	Farnborough	WTT	60 fps	15	48	–	F.O.	(1) .778	(2) .863	2	F.O. = full open
		U. K.				L_s =		.53	.738	.816		
						120"		.424	.554	.613		
						L_s/D_o		.318	.434	.480		
						= 0.67		.212	.288	.319		
								.106	.090	.117		
								.053	.042	.046		
SF 4	1960	Farnborough	WTT	60 fps	8.7	10	–	.22	0.295		2	
		U. K.		80 fps					0.262			
				60 fps				.33	0.554			
				80 fps					0.528			
				60 fps				.44	0.741			
				80 fps					0.714			
				60 fps				.55	0.922			
				80 fps					1.00			

TABLE 1 SOLID FLAT CIRCULAR PARACHUTES SHEET 2

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D.S)_R}{(C_D.S)_o}$	Ref	Comments
SF 5	1963	Ames 40/80 Ft W. T.	WTT	5.4 (1) 10.4 15.0	28	28	-	.08	0.0365 0.0311 0.0246	7	(1) Dynamic Pressure
				5.8 (1) 10.2 15.0	28	28		.13	0.0925 0.0958 0.0970	7	
				5.4 (1) 10.2 15.2	28	28		.18	0.131 0.133 0.135	7	
SF 6	1963	Wright-Patterson AFB	WTT	100 fps	1.99	24		0.2 0.3 0.5 0.62 (2)	0.236 0.310 0.646 1.0	10	
SF 7	1964	Wright-Patterson AFB	WTT	35 fps	1.5	24		0.172 0.282 0.366 0.466 0.62 (2)	0.208 0.273 0.344 0.481 1.0	11	(2) Full open

TABLE 1 SOLID FLAT CIRCULAR PARACHUTES SHEET 3

Test Series	Date	Location	Type of Test	Dynamic Pressure psf	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D.S)_R}{(C_D.S)_o}$	Ref	Comments
SC 1	1963	NASA Ames 40/80 Ft Wind Tunnell	WTT	5.6 10.1	24	24	—	0.08	0.059 0.056	7	
				5.85 10.3 15.05				0.13	0.106 0.107 0.110	7	
				5.36 10.12 15.17				0.18	0.150 0.152 0.155	7	
STC 1		El Centro	DFFT	80 - 120	76	72	4	0.066	0.153(min) 0.184(av) 0.215(max)	13	Total of 13 tests
STC 2		El Centro	DFFT	95 - 129	100	92	4	0.064	0.0195 0.0184	13	V_{e_o} = 17.0 ft/sec V_{e_o} = 21 ft/sec

TABLE 2 SOLID CIRCULAR CONICAL PARACHUTES

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
ES 1	1964	El Centro	DFFT	130 Kn	35	30	4	0.301	0.318 0.330 0.347	8	All ES-type parachutes are 10 percent flat extended skirt parachutes
FES 2	1959	El Centro	DFFT	Var	71	64	4	0.071	0.249 0.260 0.227 0.201 0.211	12	
FES 2	1959	El Centro	DFFT	Var	71	64	4	0.109	0.296 0.323 0.329	12	
FES 3	1959	El Centro	DFFT	Var	78	64	4	0.0665	0.255 0.204 0.165 0.204 0.144	12	
ES 4	1959	El Centro	DFFT	Var	34.5	36	2	0.0576 0.081	0.322 0.463 0.364 0.295 0.372	12	

TABLE 3 EXTENDED SKIRT PARACHUTES SHEET 1

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
ES 5	1964	Wright-Patterson AFB	WTT	35 fps	1.5	24	-	0.172 0.282 0.366 0.466 0.62(1)	0.25 0.308 0.379 0.515 1.0	11	(1) Full open parachute
FES 6	1964	Wright Patterson AFB	WTT	35 fps	5	24	-	0.172 0.282 0.366 0.466 0.62(1)	0.212 0.290 0.386 0.515 1.0	11	
ESS 7(2)	1964	Wright-Patterson AFB	WTT	35 fps	1.5	24	—	0.172 0.282 0.366 0.466 0.62(1)	0.186 0.232 0.315 0.441 1.0	11	(2) 10 percent straight extended skirt parachute
ES 8	1963	Wright-Patterson AFB	WTT	100 fps	1.9	24	-	0.2 0.3 0.5 0.62(1)	0.252 0.353 0.603 1.0	10	

TABLE 3 EXTENDED SKIRT PARACHUTES SHEET 2

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
RS 1	1964	El Centro	DFFT	200-360 Kn	17.7	20	6	0.08 0.127	0.05 0.075 0.086	14	
RS 2	1963	Wright-Patterson AFB	WTT	100 fps	1.89	24	—	0.20	0.23 to 0.32	10	8 tests total
								0.30	0.376 to 0.48	10	5 tests total
								0.5	0.76 to 0.80	10	4 tests total
								$0.62^{(1)}$	1.0		
RS 3	1964	Wright-Patterson AFB	WTT	35 fps	1.5	24	—	0.172 0.282 0.366 0.466 $0.62^{(1)}$	0.221 0.282 0.366 0.466 1.0	11	

(1) Full open parachute

TABLE 4 RINGSLOT PARACHUTES

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
RRS 1	1966	El Centro	DFFT	120 to 180 Kn	85.5	68	4/8	0.08 (1) " 0.096 0.21 (2) 0.23 0.24 0.26	(F) (D) 0.052/0.07 0.056/0.062 0.20 /0.21 0.218/0.224 0.224/0.250 0.220/0.276	4	Apollo II (H) main parachutes refer to first and second reefing stages (F) is initial and (D) is final reef opening
RRS 2	1963	NASA Ames 40/80 Ft Wind Tunnel	WTT	3.4 psf 10.4 " 15.2 " 18.4 " 9.7 " 11.4 " 20 "	28	72	–	0.13 " " " 0.18 " "	0.123 0.128 0.129 0.126 0.181 0.185 0.178	7	Scale model of Apollo I 88 ft diameter parachute
RRS 3	1963	NASA Ames 40/80 Ft Wind Tunnel	WTT	10 psf	44	72	–	0.08 0.13 0.18	0.0875 0.166 0.221	7	Scale model of Apollo I 88 ft D_o parachute
RRS 4	1972	El Centro	DFFT	150 to 300 Kn	70	64	–	0.06 0.075 0.10	0.031 0.051 0.077	15	B-1 main parachute

TABLE 5 RINGSAIL PARACHUTES SHEET 1

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
RRS 5	1959	El Centro	DFFT	150 to 180 Kn	63	48	4	0.11	0.055	4	Mercury Spacecraft Main Parachute
									0.058		
									0.066		
									0.072		
								0.125	0.070		
									0.076		
RRS 6	1963	NASA Ames 40/80 Ft Wind Tunnel	WTT	10–14 psf	88	72	—	0.08	0.0732	7	Apollo I Main Parachute
									0.0735		
								0.13	0.110 (1)		
								0.18	0.14 (1)		(1) Mid-Gore Reefing
								0.13	0.081 (2)		
								0.18	0.122 (2)		(2) Skirt Reefing

TABLE 5 RINGSAIL PARACHUTES SHEET 2

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
RC 1	See Appendix A										
RO 2	1954	El Centro	SFFT	110 to 180 fps	64	84	—	0.034	0.0217	17	Minimum reefing
								0.106	0.162		
									0.168		
								0.139	0.208		
									0.217		
								0.18	0.242		
									0.273		
								0.373	0.59		
									0.596		
									0.603		
								0.433	0.658		
									0.668		
									0.683		
									0.739		
								0.51	0.815		
									0.995		
								0.62	1.0		Full open
RO 2A	1954	El Centro	SFFT		64	84	—	0.139	0.137	17	High porosity canopy with marginal inflation
									0.124		
									0.125		
									0.135		

TABLE 6 RIBBON PARACHUTES SHEET 1

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D.S)_R}{(C_D.S)_o}$	Ref	Comments
RO 3	1953	El Centro	SFFT		16	20	—	0.055	0.032	18	
									0.022		
								0.155	0.043		
								0.14	0.120		
									0.136		
								0.224	0.232		
									0.247		
									0.291		
								0.39	0.548		
									0.558		
								0.61	0.975		Full open
									1.10		
									1.15		
RO 3	1953	El Centro	SFFT		20	24	—	0.032	0.038	18	
									0.026		
								0.085	0.048		
								0.119	0.11		
									0.136		
									0.148		
								0.23	0.286		
									0.311		
									0.318		

TABLE 6 RIBBON PARACHUTES SHEET 3

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
RO 3	1953	El Centro	SFFT		12	16	—	0.0437	0.054 0.055	18	
								0.133	0.104 0.108 0.117 0.122	18	
								0.22	0.244 0.252 0.262	18	
								0.383	0.532 0.55 0.568	18	
								0.479	0.757 0.775	18	
								0.60	0.83 0.86 0.97 1.02 1.07 1.11 1.12	18	Full open

TABLE 6 RIBBON PARACHUTES SHEET 2

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
RO 3	1953	El Centro	SFFT		20	24	—	0.396	0.443 0.555 0.58 0.66	18	
								0.62	0.93 0.98 1.08		Full open
RO 3	1953	El Centro	SFFT		40	44	—	0.039	0.038 0.028		
								0.24	0.228 0.243		
								0.415	0.515 0.565		
								0.64	0.94 1.06		Full open

TABLE 6 RIBBON PARACHUTES SHEET 4

Test Series	Date	Location	Type of Test	Speed mph	Parachute D_o Ft	Parachute N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D \cdot S)_R}{(C_D \cdot S)_o}$	Ref	Comments
RO 4	1951	Wright Field 20 Ft Wind Tunnel	WTT	100	3.0	12	—	0.58	.992	19	Full open
				150					1.005		
				200					1.0		
				240					1.01		
				100				0.435	0.651		
				150					0.665		
				200					0.675		
				100				0.354	0.535		
				150					0.555		
				200					0.554		
				100				0.297	0.440		
				150					0.446		
				200					0.434		
				1C0				0.208	0.316		
				150					0.318		
				20C					0.302		

TABLE 6 RIBBON PARACHUTES SHEET 5

Test Series	Date	Location	Type of Test	Speed	Parachute D_o Ft	N_{SL}	TR sec	Reefing Ratio D_R/D_o	$\frac{(C_D.S)_R}{(C_D.S)_o}$	Ref	Comments
RO 8	1964	Wright-Patterson AFB	WTT	35 fps	1.5	24	—	0.172 0.282 0.366 0.466 0.62	0.188 0.394 0.544 0.73 1.0	11	
RC 9	1964	Wright-Patterson AFB	WTT	35 fps	1.5	24	—	0.172 0.282 0.366 0.460 0.62	0.216 0.384 0.525 0.684 1.0	11	
RO 10	1963	Wright-Patterson AFB	WTT	100 fps	1.9	24	—	0.2 0.3 0.5 0.62	0.229 0.386 0.783 1.0	10	

TABLE 6 RIBBON PARACHUTES SHEET 6

APPENDIX A

REEFING TESTS WITH A CONICAL RIBBON PARACHUTE OF 13.4 FOOT DIAMETER TOWED BEHIND A DC-130 AIRCRAFT

Tests were conducted by the USAF 6511th Test Group at the Department of Defense Joint Parachute Test Facility at El Centro, California, in 1960 with a 13.4 foot diameter drogue chute for the US Army USD-5 (Fairchild M-252) Recon drone.

The parachute was a 25 degree conical ribbon parachute with 20 suspension lines of 2250 pounds strength each, a suspension line length of 13.4 ft ($L_s/D_o = 1.0$) and a total canopy porosity $\lambda_T = 25.4\%$

The parachute was towed behind a DC-130 aircraft on a 100 foot tow line. Loads were measured with strain gages and the airspeed with a calibrated airspeed indicator. The airspeed was changed in steps from 120 KIAS to 200 KIAS. The installed length of the 2250 pound reefing line was measured under 20 pound tension.

Table 7 gives a summary of measured and calculated data. Figure 12 shows drag area ratio ϵ vs reefing ratio τ. Figure 10 gives the average drag area ratio for each reefing ratio.

APPENDIX B

REEFING TESTS WITH A 3.0 FOOT DIAMETER FLAT RIBBON PARACHUTE FOR THE X-2 RESEARCH AIRCRAFT IN THE WRIGHT FIELD 20 FOOT WIND TUNNEL

The USAF X-2 research aircraft was equipped with an ejectable nose section. In an emergency the pilot would eject the nose section and an automatically deployed drogue chute would stabilize and decelerate the nose section. After descending to 5000 feet above ground, the pilot would manually leave the nose section and descend with a standard 28 foot man-carrying parachute.

Tests were conducted in 1950 in the Massie Memorial 20 foot diameter wind tunnel at Wright-Patterson AFB to determine the parachute size required to stabilize the nose section and the reefing characteristics of this parachute. A 3/8 scale, dynamically similar, X-2 nose section was installed in the tunnel test section, free to oscillate around its pitch axis. In tests, the nose section would stabilize in the airstream at an angle of attack of approximately 70 degrees. A three foot diameter flat ribbon parachute reefed to various drag areas was then deployed and the minimum drag area determined necessary to stabilize the nose section close to zero angle of attack. It became clear in these tests that the desirable pitch angle for parachute descent was not the zero angle of attack, but the zero lift angle with the parachute force line passing through the C.G. of the nose section.

Prior to the nose section stabilization tests, the parachute was tested at various reefing stages at speeds varying from 100 mph to 250 mph. The results of these reefing tests are tabulated in Table 6, sheet 5. It will be of interest that in subsequent free-fall tests, the 3/8 scale nose section spun at an angle of attack of approximately 70 degrees. Deploying the drogue chute, selected in the wind tunnel tests, stabilized the nose section.

In actual flight tests, the X-2 research aircraft had an emergency and the pilot ejected in the nose section. The subsequent investigation showed that the drogue chute opened at high supersonic speed, stabilized, and decelerated the nose section as designed.

Data on this system were never published due to the specialized nature of the project.

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